Meeting Residual Heat Loads in a Passivhaus Using Solar Energy and a Seasonal Store

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Abstract
A house constructed to the Passivhaus standard, situated in Co. Galway, Republic of Ireland, has seen the heating season for an Irish dwelling drop from a predicted eight months to two. The Passivhaus has a (low) predicted demand for heating between October and May of 1832 kWh, and a year round demand for domestic hot water. To meet these needs a 10.6m^2 evacuated tube collector was installed on the south-facing roof. This feeds the DHW tank, underfloor and air space heating and a 23m^2 sensible seasonal store buried in the garden. This paper reviews performance of the installation over an 18 month period.

A space heating Solar Fraction of 0.72 was achieved for the heating season from September 2010 to April 2011. The seasonal store provided a significant 556kWh of energy in 2010, despite losing 50% of the peak stored energy of 1111kWh through sensible heat losses. The financial analysis shows that direct solar heating combined with the ISES is the most economical solution for heating especially when the proposed UK RHI incentive is considered.

Keywords Inter Seasonal Energy Storage (ISES), Passivhaus, Low Energy Housing, Solar Fraction, Renewable Heat Incentive (RHI)

1.0 Introduction.
There is significant potential afforded by solar assisted space heating in Northern maritime climates [*i*,*ii*,*iii*]. This reflects the fact that the usefulness of Solar Space Heating is a function of the amount of heating required and its pattern. Temperate maritime climates have a long heating season, coupled with mild winters and consequently a relatively high solar saving compared with countries for example with a continental climate which have a relatively short but high demand heating season.

As part of the EU funded CEPHEUS (Cost-Effective Passive Houses as EUropean Standard) project [*iv*], 221 housing units complying with the Passivhaus standard were built in five European countries and their operation was evaluated. The project demonstrated that space-heating demand can be reduced to less than 15 kWh/(m^{2}a) through the application of the *Passivhaus* standard. This represents a reduction of between 80 - 90% compared with the building regulations requirements pertaining at the time of the study. Given the low space heating demands of a Passivhaus, solar thermal energy can make a significant contribution to meeting the residual heating needs, especially in temperate maritime climates [*iii*].

2.0 Viability of seasonal thermal energy storage

Once the precursor of ensuring a low heat demand is in place, consideration can be given to optimising the collection and storage of a renewable energy source such as solar.

Roth & Broderick [*v*] recognised the advantages of saving low-cost heat using a Seasonal Thermal Energy Store (STES).

The most common seasonal thermal energy stores are Aquifer Thermal Energy Stores (ATES) and Borehole Thermal Energy Stores (BTES). However both of these require suitable ground conditions that do not always exist [*vi*]. The size of STES is also important to consider, as efficiency and economic viability improve with scale with encouraging results reported by authors such as Schmidt et al [*vii*]. This suits countries where community-based heating systems are common such as the Netherlands, which currently has the largest number of STES installations in Europe [v]. However, the largest proportion of houses built in Ireland are detached dwellings (54.2% and 45.7% respectively for 2010 and 2009) [*viii*], and a significant proportion of houses in the UK are detached (up to 27%) [*ix*].In addition, detached dwellings also often afford the advantage of providing sufficient land for the installation of a seasonal thermal energy store. Thus, for the UK and Ireland, consideration needs to be given to how best to provide seasonal thermal energy storage for the single dwelling. Further, rural housing tends to be dominated by detached dwellings, affording land availability, and also restricted by the lack of grid-connected gas [xii].

3.0 Installation Description

3.1 Overview of Installation

A manufacturer of Passive Homes, built a Passivhaus show home of 215m^2 in Galway in 2005 (figure 1). The house has a very low space heating demand of 1832kWh (as determined by the Passive House Planning Package - PHPP [*x*]), when it is used as a residence for a family of five. The house is primarily used as an office and show house, but is also inhabited approximately three times per annum for up to three weeks at a time. In June 2009, an underground aqueous Seasonal Thermal Energy Store was installed in order to investigate the possibilities afforded by the exceptionally low space heating demands of the *Passivhaus*. The system was to be used to supplement the electric space heating and lead to an increase in the solar fraction for the house.

The University of Ulster has gathered empirical data in order to supplement theoretical research in the area and monitored the performance of the Seasonal Store installation. This was carried out as part of a PhD thesis investigating the application of thermal energy storage to the Passivhaus standard in the Irish climate [*xi*]. The data that has been gathered was used to validate a computer model of the installation, which has been tailored to the Irish climate. This is being used to assist with scenario planning and in turn drive the optimisation of Irish Seasonal Thermal Energy Storage Systems, which is the subject of another paper.

Figure 1. House with Solar Collectors and Seasonal Energy Store

An Evacuated Tube Solar collector array, of 10.6m^2 aperture, visible in Figure 1, collects diurnal heat and stores it indirectly in a 300 litre domestic hot water (DHW) cylinder (“Tank 1”) via a heat transfer coil, see figure 2. Once the temperature at the base of the DHW tank reached 65°C, (under the initial configuration – see later), a three way valve diverted the solar heated fluid via a heat exchanger coil, to a subterranean Seasonal Store tank (“Tank 2”) of capacity 22,730 litres, which is located in the garden, see figure 3. The water in Tank 2 is not circulated and is used purely as an indirect sensible heat store.

DHW hot water for domestic use is drawn directly from the top of Tank 1, whereas the water in Tank 2 indirectly heats the domestic hot water supply via a pre-feed heat exchanger coil in Tank 2 and also the space heating system via the underfloor and air duct heating systems. Due to the design employed, thermal stratification does not occur to any great extent in Tank 2, with the temperature difference between the top and bottom of the tank rarely exceeding 2°C. This arrangement ensures, a) the solar fraction for DHW is exceptionally high, and b) heat surplus to the DHW need is stored for winter use, ensuring the space heating Solar Fraction is increased. The cycle commences in January with the lowest tank temperature and finishes the following January once the summer solar energy has been captured and utilized over December and January.

3.2 Description of Monitoring Equipment

The objective of the monitoring was to; a) determine key performance parameters such as solar fraction, solar yield etc for the installation, and b) examine means of improving the efficiency of the installation by investigating tank thermal stratification and thermal losses from the tank and pipework etc. In order to do this a total of 67 sensors were installed to monitor Tank 2 and its performance in relation to the space heating demand. In addition, basic information was gathered on environmental conditions and on other components, such as Tank 1, in order to provide a full picture of the energy balance and flows.

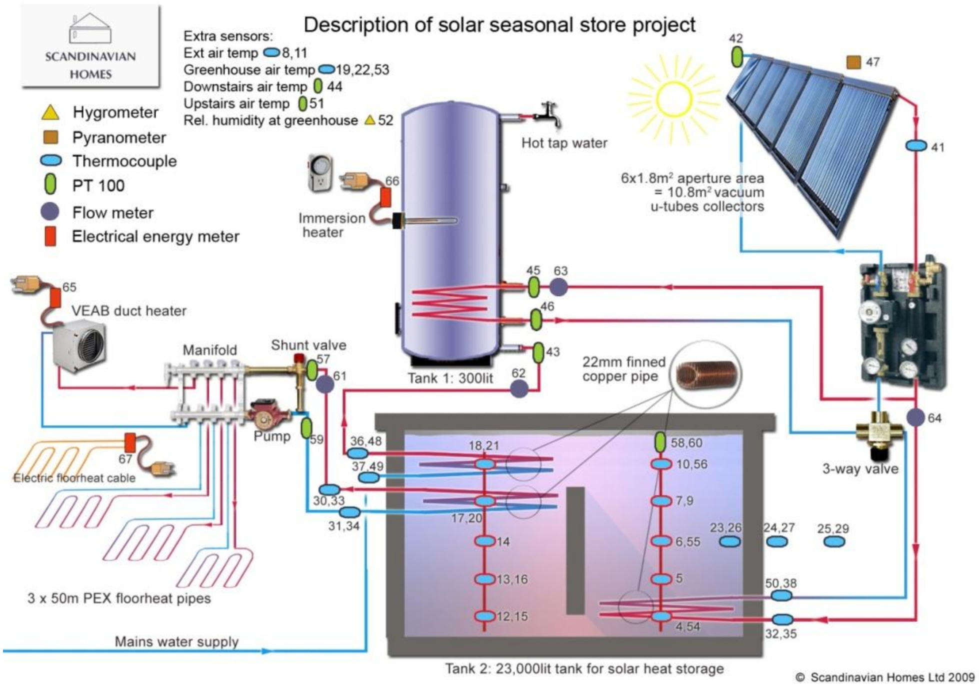


Figure 2: Schematic of the water system showing the position of sensors [xii]

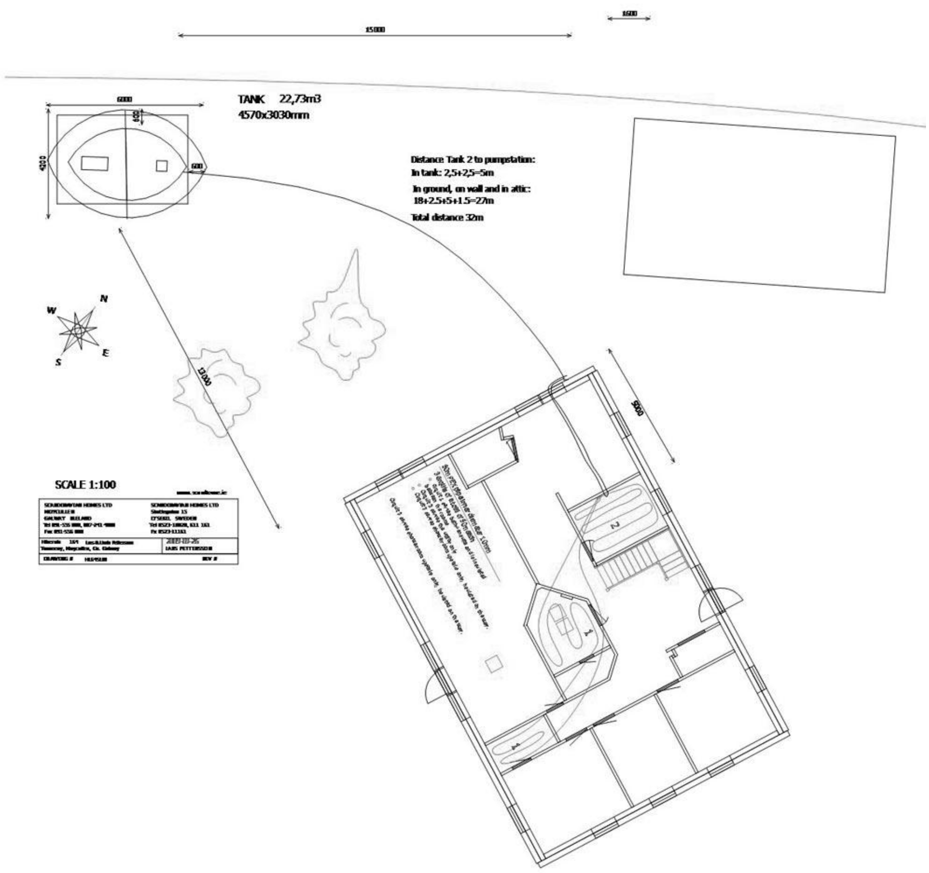


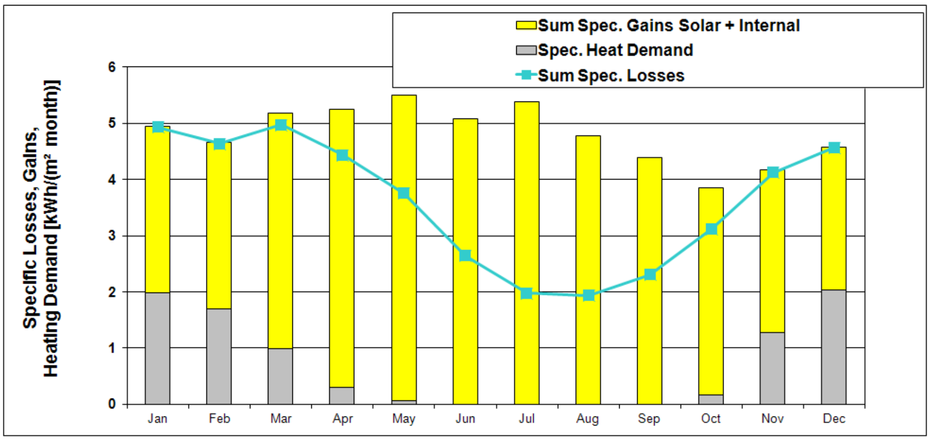
Figure 3. Location of the Seasonal Store and Underfloor Heating System Pipe Runs [xii].

Data from the installed sensors was sampled every 10 seconds, averaged and then recorded every 6 minutes using a multi channel logger, with data retrieved weekly via an Internet connection and downloaded to an off-site persistence layer. In excess of 10,000 individual data measurements were taken on a daily basis and amalgamated into a monthly spreadsheet from which the required calculations were made.

4.0 Residual Heat Loads

For the house in Galway the Passive House Planning Package predicted a total heat loss of 6472 kWh pa which would be met with solar and internal heat gains totalling 4640 kWh pa and a residual heat load of 1832 kwh pa.

Figure 4 below shows the balance between heat losses and gains and the resulting heat demand on a monthly basis per square metre of treated floor area.



Annual Heat Demand: Comparison				
EN 13790 Monthly Method	1832	kWh/a	8.5	kWh/(m²a) Reference to habitable area
PHPP, Heating Period Method	1940	kWh/a	9.0	kWh/(m²a) Reference to habitable area

Figure 4 Specific Losses, Gains and Heating Demand for House in Galway

4.1 Predicted heating season

Figure 5 and table 1 below show the predicted space heating demand and the solar resource available from the 10.6 m² solar panels for the Passivhaus built in Galway, Ireland. The figures are produced using the Passive House Planning Package and are tailored by using the efficiency figures for the solar collectors used on the site.

The heating season in Ireland is year round with the heating season for homes according to degree day data in Ireland being 10 months. For the Passivhaus under study the heating season is significantly lower, with three months requiring less than 100 kWh of space heating, but heating is still required for 8 months of the year.

It can be seen that the total solar resource available from the 10.6 m² of solar panels is 4317 kWh, compared with the space heating demand of 1832 kWh. Thus there is a surplus of 2485 kWh available for use or storage on an inter-seasonal basis. If stored efficiently this could meet a significant part of the load.

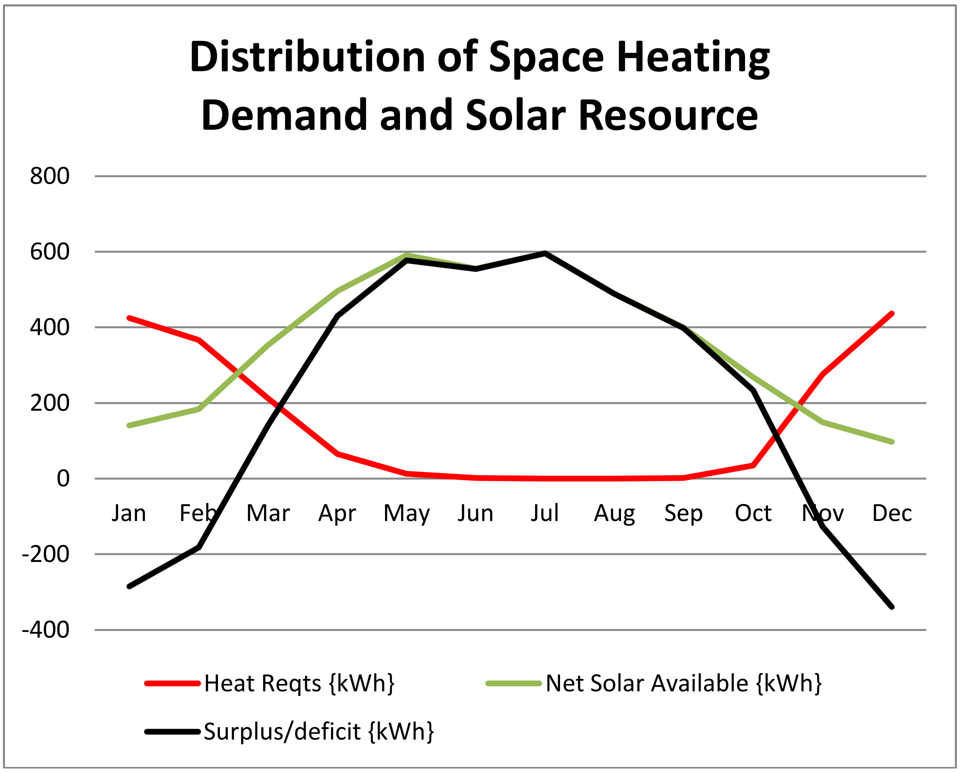


Figure 5 Graph of Predicted Space Heating Demand and Solar Resource

Dublin						**Specific Space Heating Demand**	**8.5**	**kWhr/m2/a**				**Frequency of Overheating**	**0**	
					Months requiring heating	**10**							**No. of mths where solar contributes >10% of space htg reqt**	**10**
			Months requiring >10kWhr htg			**8**								
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Heat Reqts {kWh}		425	366	213	65	13	1	0	0	1	35	276	436	1832
Incident Solar {kWh/m2}		38	50	96	135	161	151	162	133	109	73	41	26	1174
Net Solar Available {kWh}		140	184	353	496	590	555	596	489	400	268	149	97	4317
Surplus/deficit {kWh}		-285	-182	140	430	578	554	596	489	398	234	-127	-339	2486
% of Dmd met		33	50	166	758	4578	39863	0	0	29944	775	54	22	236

Table 1 Predicted Space Heating Demand and Solar Resource for MOYCULLEN Passivhaus

4.2 Actual space heating demand & Solar Fractions

4.2.1 Calendar Year 2010

The top row of table 1 shows that the space heating requirements for the Passivhaus in Galway totalled 1198 kWh for the calendar year 2010. This is lower than the 1832 kWh predicted by the Passive House Planning Package, and reflects the usage as an office and show house rather than as a dwelling.

The domestic hot water demand throughout the year totalled 852 kWh which is significantly lower than the UK average of 1703 kWh reported by Martin [*xiii*]. Of this 793 kWh was met using the solar resource. This gives a domestic hot water solar fraction of 0.93, which is exceptionally high, but again the use of the house as an office must be considered.

The recorded space heating demand for 2010 was 1198 kWh. Of this 556 kWh was met by the solar store, representing 46% of the space heating need. It can be seen from the table that the energy drawn from the solar store in October, November and December made a significant contribution in decreasing the heating season by two months.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Heating Reqts {kWh}	291.29	223.60	120.31	69.59	0.00	0.00	0.00	0.00	0.00	36.58	86.80	369.96	1198.14
Incident Solar Rad {kWh/m2}	46.32	61.64	66.66	148.16	146.10	148.43	125.59	138.25	109.04	69.30	40.12	42.08	1141.69
Net Solar collected {kWh} 10.6m2 (Dir Sp Htg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.83	102.62	116.45
Solar store Space Htg Contribution {kWh}	0.00	0.00	113.91	69.42	0.00	0.00	0.00	0.00	0.00	36.57	69.09	267.33	556.32
Store (+/-) {kWh} (Net)	78.00	125.15	414.91	329.82	323.31	199.23	-21.01	96.33	-106.66	-188.09	-301.44	-484.03	465.51
% of Space htg Demand met by solar	0.00	0.00	0.95	1.00	n/a	n/a	n/a	n/a	n/a	1.00	0.96	1.00	0.56

Table 2 Recorded heating demand, solar resource and space heating contribution from solar Calendar Year 2010

4.2.2 Heating Season 2010/2011

The configuration of the installation was changed in November 2010 to allow heat from the solar panels to be distributed within the house through the heat recovery and ventilation (HRV) system. For December (the first full month of operation of direct solar space heating), Table 2 illustrates that of the 369 kWh space heating demand, 102 kWh was provided directly by solar. This gives a solar fraction for December of 28%, versus the predicted solar fraction as per table 1 of 22% for the month of December. This was a very good result considering Galway was subject to very cold temperatures in December 2010.

4.3 Level of Comfort

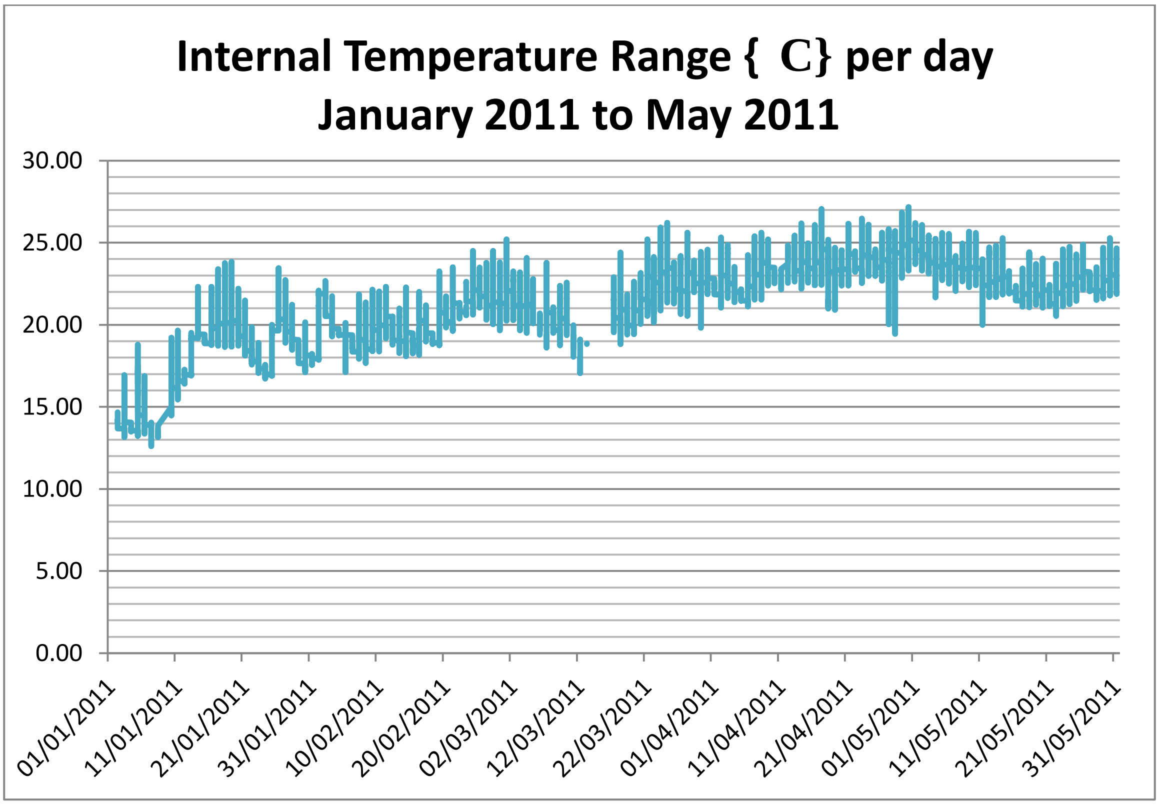


Figure 6 Internal Temperatures for the First Five Months of 2011

Figure 6 shows that temperatures of less than 15°C were experienced in the first 10 days of January, during which time the house was not occupied. Thereafter the internal temperatures always exceeded 17°C, even during periods when the house was unoccupied.

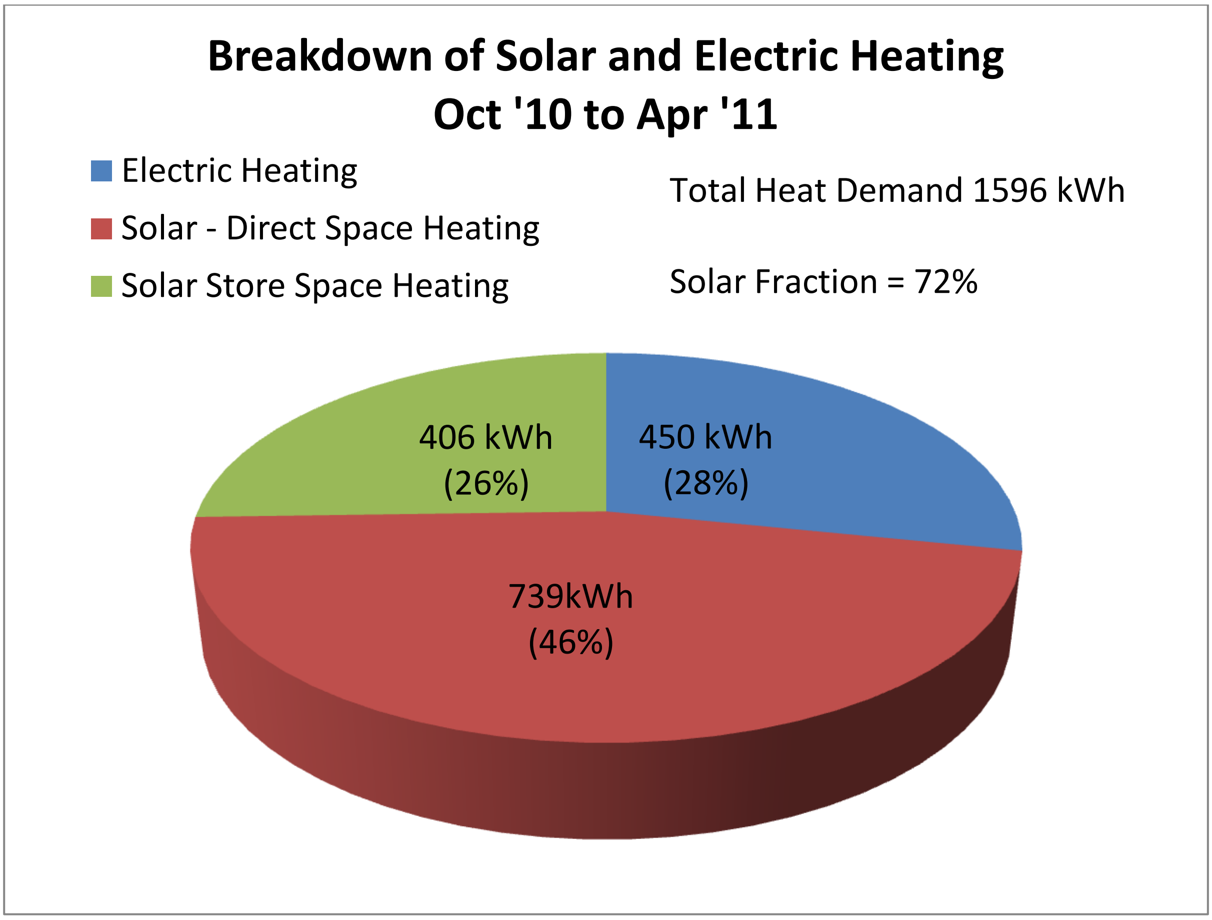


Figure 7 Breakdown of Solar and Electric Heating Contribution to Heating Demand Oct 2010 to Apr 2011

Figure 7 above shows that of the total space heating demand of 1596 kWh between October 2010 and April 2011, only 450 kWh was borne by the electric heating system. The solar fraction of the heating season is seen to be 72%, with 739 kWh (46%) of the total space heating demand being met by direct space heating, and the remaining 406 kWh (26%) by means of inter seasonally stored heat. It is noted that the Passive House Planning Package (PHPP) forecast that the annual space heating demand would be 1832 kWh, 236 kWh above the recorded space heating demand, reflecting the pattern of use as an office rather than a permanent residence.

Figure 8 shows that only January and February required a statistically significant amount of electric heating, demonstrating that the space heating needs were met either by solar space heating via underfloor or the Heat Recovery and Ventilation (HRV) system or via stored solar heat for all but two months of the year. It is noted that the lowest solar fraction recorded was that of 31% in January 2011 and that 56% of the space heating demand was met by solar energy in February 2011.

Figure 9 shows the breakdown on a per month basis between electric heating, direct solar space heating and stored solar space heating for the heating season ’10 to ’11.

It can be seen that the Inter-Seasonal Energy Store made a significant contribution in October, November and December, but was depleted by January 2011. It should be noted that on 26 November 2010 the fluid to air heat exchanger was connected to the existing HRV system in the house. This enabled solar heat collected by the 10.6 m² solar array to be input directly to the house air heating system as previously detailed.

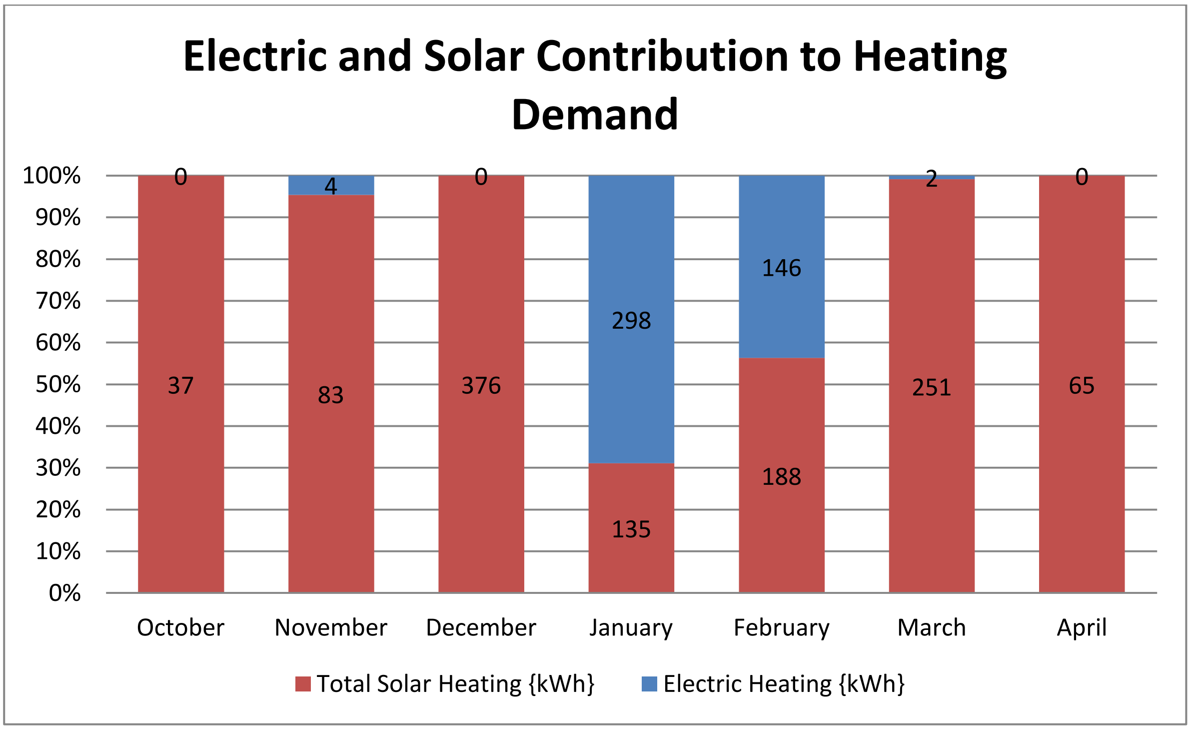


Figure 8 Breakdown of Total Space Heating Demand Showing Solar Fraction per Month

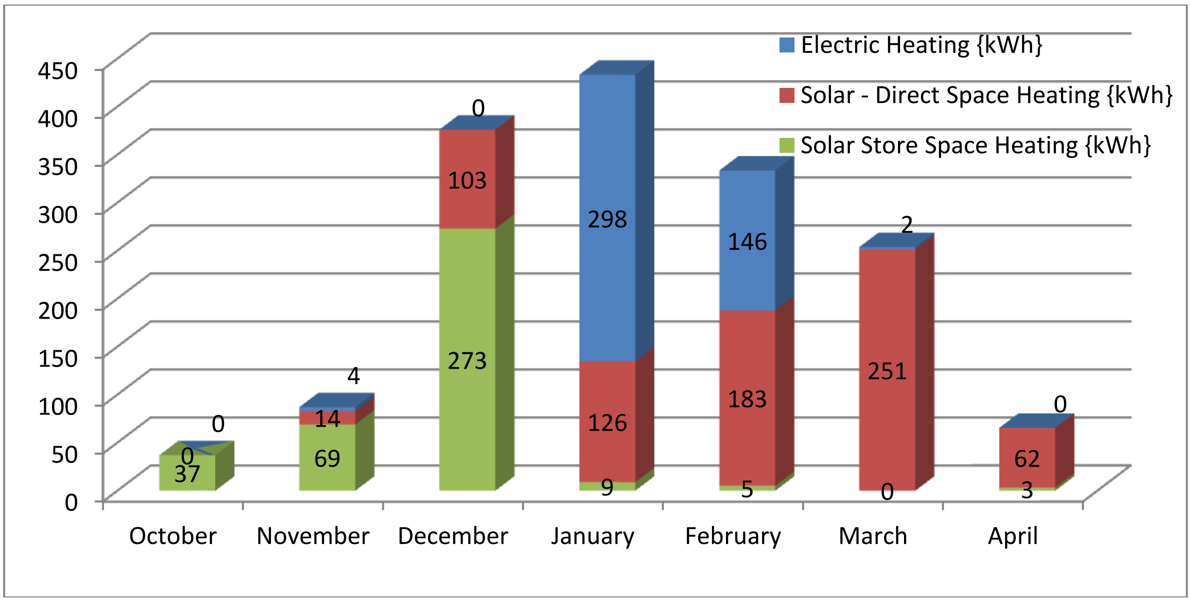


Figure 9 Breakdown of Electric, Direct Solar, and Stored Solar Space Heating on a per Month Basis, October 2010 to April 2011

It is anticipated that the facility to use collected solar heat directly in the air heating system will significantly reduce the demand on the ISES for the winter months.

5 Solar System and Inter Seasonal Energy Store Performance

5.1 Energy Storage Capability of the Seasonal Energy Store

The total energy capacity of the sensible heat store is given by

$$E = mc_p\Delta T \text{ \{Joules\}} \qquad \text{eq 1}$$

where, E is the Energy in joules, m is mass, expressed in kg, c_p is the specific heat capacity, with units of J/kgK and ΔT is the temperature differential over which E is being calculated.

Assuming that tank 2 can be heated to 85°C by the end of the summer and that the minimum useful temperature for the underfloor heating system is 25°C, the quantity of useful stored heat is;

Q = 22730 litres x 4.181 kJ/kg x (85 – 25) °C = 5.71 MJ or 1586 kWh

5.2 Recorded Mean Bulk Tank Temperatures

Figure 10 shows the recorded Mean Bulk Tank Temperatures (MBTT) at the site in Galway for 2010. The maximum temperature achieved was 67.1°C on 5 September 2010, and the temperature on 31 December was recorded at 23.7°C. These are lower than predicted due to user intervention and lower temperature rises and higher heating demand due to the climatic conditions experienced:

- Heat was drawn from tank two during the months of March (114kWh) and April (69kWh), providing 95% and 100% of the space heating needs respectively. The total resource drawn was calculated at 183kWh, equivalent to a reduction in the tank capacity of 215 kWh, given system losses of 17.6% (see section below). Considering that a rise in temperature of 1°C in tank two is equivalent to 26.4 kWh of energy, the temperature rise forgone due to this drawdown s in excess of 8°C.

- On 24 June, an ESB electricity outage occurred and the temperatures at the solar array exceeded 150°C, as the pump did not operate to draw the heat from the solar array. A leak was discovered on the roof on 25 June which required solar fluid to be topped up. The house was then left vacant until 25 August. Onside records are not detailed, but a system intervention was required on-site at the end of August. Following this, figure 5 shows that tank temperatures again started to increase.

- July was the dullest on record resulting in lower than anticipated sunshine and hence lower temperatures in tank two

- In November the lowest temperatures experienced since 1985 were recorded at most Irish Met Office locations, with some experiencing the lowest temperatures on record. Claremorris (the closest location to Moycullen) recording temperatures on average 1.3°C below normal.

- December experienced the lowest temperatures on record at most Met Office Locations with Claremorris (the closest location to Moycullen) recording temperatures on average 5.5°C below normal.

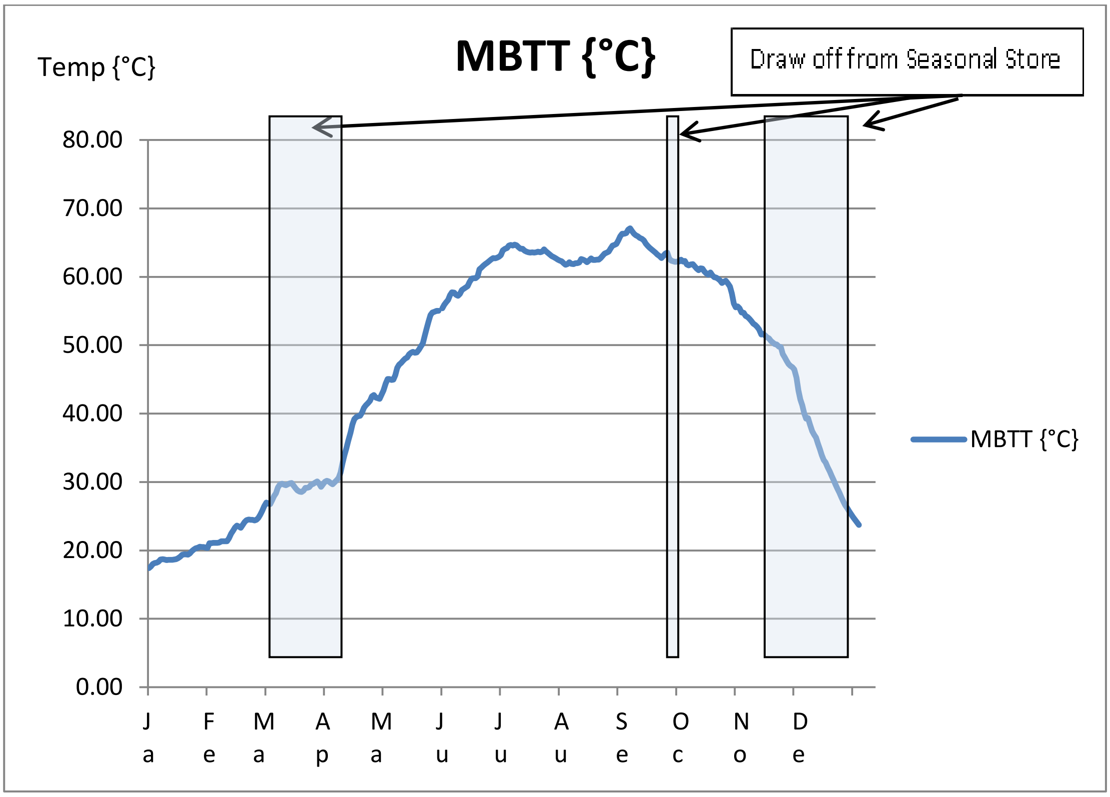


Figure 10 Mean Bulk Tank Temperatures Recorded for 2010

5.3 Heat Loss and Efficiency Calculations for the Seasonal Store

Tanks losses form a significant factor in the performance of the Seasonal Energy Store, as can be seen from the forecast figures shown in Table 3 below. From the figures obtained from two cool down tests, the heat loss co-efficient *Uz* was calculated as 10 W/K. Using Eq 2 below the tank loss was calculated and the results presented in table 4.

Tank Loss = $\Delta T * Uz * 24 / 1000$ {kWh}, Eq 2

Where *Uz* is the heat loss coefficient, and *ΔT is the reduction in temperature*

Month	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Ave MBTT {°c}	19.00	22.90	28.90	36.30	48.90	59.40	63.70	62.90	64.50	59.90	50.40	31.90
Soil Temp {°C}	6.10	8.00	9.10	11.30	14.60	18.20	19.90	20.60	19.60	17.80	14.10	9.70
Tank Losses {kwh}	92.88	107.28	142.56	180.00	246.96	296.64	315.36	304.56	323.28	303.12	261.36	159.84
Potential Daily Temp Loss {°C}	0.12	0.13	0.18	0.23	0.31	0.37	0.40	0.38	0.41	0.38	0.33	0.20

Table 3 Actual Heat Loss per month for 2010

The heat losses over the period of the year amount to 2744 kWh. The maximum peak useful heat stored in the Seasonal Store occurred when the store achieved 67.1°C, giving a usable range of 67.1°C - 25°C, or 42.1°C. At 26.4kWh/°C, this is equivalent to 1111.4 kWh. The efficiency of the seasonal thermal energy store, defined as the portion of heat transferred into the STES which remains available to meet loads is therefore:

Efficiency of STES = 465kWh/1111.4 = 41.8%

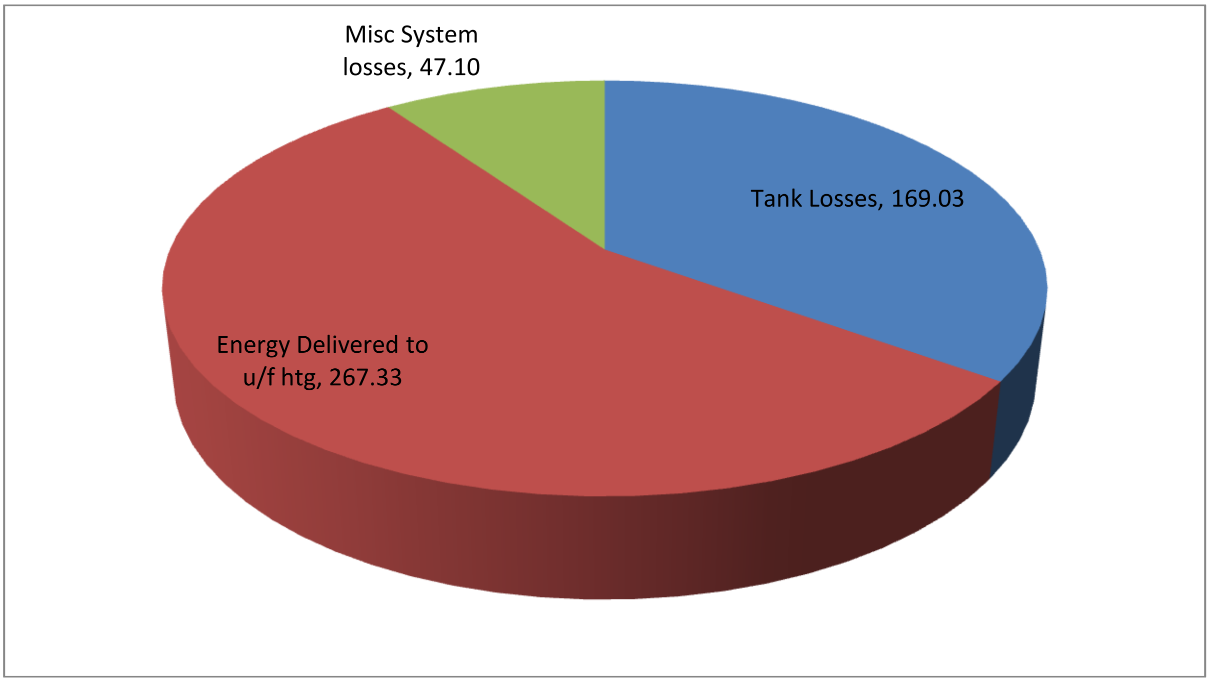


Fig 11 Breakdown of Energy Reduction of 483kWh in Tank 2 for December 2010

Figure 11 shows the breakdown of the energy reduction in tank two for the month of December. Tank losses amounted to 169kWh, while of the 267kWh delivered to the underfloor heating system, 47.1 kWh (17.6%) was lost due to system losses in transferring heat from the heat exchanger in tank two through the buried pipework to the underfloor heating system in the house.

6.0 System costs

Table 4 gives a breakdown of the total DHW and space heating system costs for a typical system comprising a solar array, space heating integration and an ISES. The costs reflect all the components for the specific installation in Galway, but exclude the site specific costs such as felling trees, research and development costs including installation of monitoring equipment along with associated installation of power and Internet connectivity, non-typical manpower costs etc.

Item	Solar DHW	Solar Space Htg	Seasonal Store
	Total cost	Extra Cost	Extra Cost
Parts	€3057.00	€2269.00	€11822.30
Labour	€1679.30	€559.77	€8956.27
Total	€4736.30	€2828.77	€20778.57

Table 4 Estimated Costs of Typical Solar DHW, Seasonal Store and Space Heating System (Euros)

The cost of the solar DHW installation (10.6m^2 solar array coupled with a 300 L tank) is considered the base system. The extra cost of a heat exchanger coil and three-way valve in order to provide for direct solar space is also detailed. Then the extra cost of a seasonal store to store surplus heat is shown.

Comparison with European CombiSystems carried out as part of an IEA task force [*xiv*] confirmed that the costs of the combi systems element of the installation is typical. The cost of the seasonal energy store shown above is for a self build system and is less expensive than more efficient stratified tanks which can be purchased. However, the cost benefit analysis undertaken shows that the self build option is attractive financially.

6.1 Net Present Value Financial Analysis

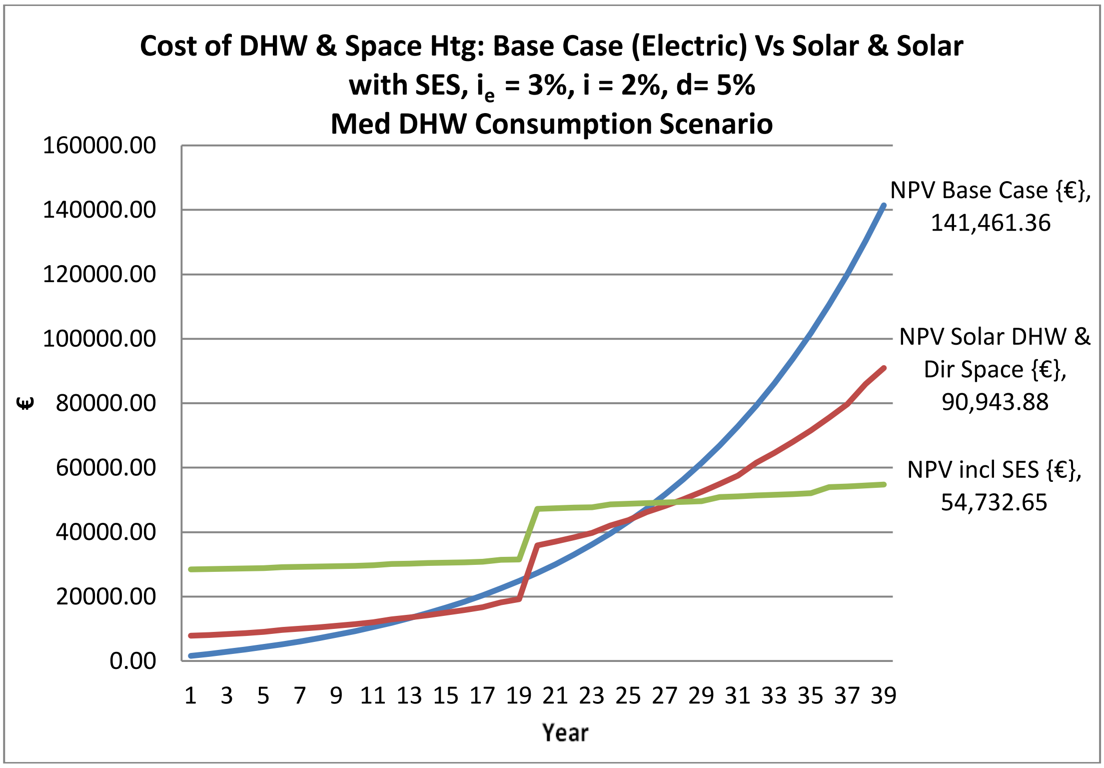


Figure 13 Net Present Value system and operation cost comparisons

An NPV financial analysis was undertaken for the typical installation costed in Table 4. In the analysis a Consumer Price Index inflation rate of 2% was used, an electricity inflation rate of 3% was used, and a discount rate of 5% was used. Analysis shows that the payback period is dependent on the domestic hot water usage scenario, and in this analysis a medium domestic hot water usage scenario is considered. The costs also include scheduled system maintenance and operating costs. In the case where the scenario of 40 years operation is considered (see figure below), it is assumed that a system overhaul of the solar collector, DHW and direct space heating and seasonal energy storage heat exchanger coils will be required at a cost equivalent to the initial investment. It is assumed that the seasonal energy storage tank and DHW tank will not require any extra investment.

Figure 13 shows that while the initial system costs are high, the total cost of providing domestic hot water and space heating is significantly lower using the solar system with integrated ISES in the long-term. The case for the ISES is all the stronger when one considers that in this analysis no terminal value was assigned to the concrete ISES.

When a conservative terminal value for the ISES is incorporated in the analysis, and a potential Renewable Heat Incentive (RHI) of 8.5p per kWh is applied, the net present value for the base case is £24,346, and for the solar system incorporating the ISES the NPV is £3837 at the end of 20 years (x).

Conclusion

The paper demonstrates the viability and potential of solar domestic hot water and space heating coupled with thermal seasonal energy storage when applied to low-energy houses in the Irish climate. An exceptionally high space heating solar fraction of 72% was achieved by totally passive means, reducing the heating season from 10 months to 4 months by virtue of director solar space heating. A further reduction of two months in the heating season was achieved through the addition of the seasonal solar thermal energy store.

It was found that the least cost option in the long-term for providing domestic hot water and space heating was to be found through the use of a solar heating system comprising domestic hot water, direct space heating and an Inter Seasonal Energy Store.

This provides a economically attractive thermal energy source option for non-gas grid connected rural dwellings in Ireland and the United Kingdom that can utilise Government grants and provide for a zero carbon alternative to wind powered electric heating. There is still a need to provide electric heating backups, which does raise the question as to future national total power generation requirements in the winter and a need for extra plant to be available for a short period of time, but this would also be the case for heat pumps.

Finally while this analysis focussed on newbuild, there is potential for the adoption of a similar approach for the retrofit market for single dwellings if the energy demand can be reduced to a level such as that required by the Enerphit standard.

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References

i Tuohy, P., McElroy, L. & Johnstone, C. 2005, "Thermal Mass, Insulation and Ventilation in Sustainable Housing - an Investigation across Climate and Occupancy".

ii Weiss, W. & Biermayr, P. 2009, *Potential of Solar Thermal in Europe*, European Solar Thermal Industry Federation.

iii Colclough S. M., Griffiths P. W., Smyth M G 2010, "Solar energy storage critical success factors for a passive houses in Ireland", *World Renewable Energy Congress XI, Abu Dhabi*.

iv Schnieders, J. & Hermelink, A. 2006, "CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building", *Energy Policy,* vol. 34, no. 2, pp. 151-171.

v Roth, K., Broderick J. 2009, "Emerging Technologies - Seasonal Energy Storage", *ASHRAE Journal,* January, pp. 41-42, 43.

vi Dincer, I. & Rosen, M.A. 2002, *Thermal Energy Storage, Systems and Applications,* John Wiley & Sons ltd.

vii Schmidt, T., Mangold, D. 2006, "New Steps in Seasonal Thermal Energy Storage in Germany", *Proceedings of Ecostock: the 10th International Conference on Thermal Energy Storage*.

viii Anon, 2011, New Houses Completed by Type, 1994 to 2010, Department of the Environment, heritage and local government, 2011 available from : http://www.environ.ie/en/Publications/StatisticsandRegularPublications/HousingStatistics/

ix English House Condition Survey, 2008 www.communities.gov.uk/housing/housingresearch/housingsurveys/englishhousecondition/

x Passive House Institute 2007, *PHPP, Passive House Planning Package*.

xi Colclough S. M., PhD Thesis, University of Ulster, 2011.

xii Courtesy of Scandinavian Homes. http://www.scanhome.ie/

xiii Martin, C. 2008, *Measurement of Domestic Hot Water Consumption in Dwellings*, DEFRA.

xiv IEA 2003, *Solar Combi Systems - European overview of installed systems 2001 to 2003*, International Energy Agency.

xii Ahern C, Griffiths PW, [2012], State of the Irish Housing Stock, paper awaiting publication.